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UNFURLABLE ANTENNA TECHNIQUES FOR HIGH-GAIN APPLICATIONS

J. C. Polk

TELEDYNE SYSTEMS Corporation
Electromagnetic Systems Division

Interim Engineering Report No. 1
1 June 1962 to 17 December 1962

Contract No. AF33(657)-8709

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ABSTRACT

This report covers the initial phases of a program for the advancement of design and fabrication techniques for unfurlable antennas for space applications. The first phase covers the design of a high-gain Cassegrain system with a spherical reflector. The effects of aperture blocking are analyzed and calculated patterns are given showing these effects. Equations for the subreflector surface are given and calculated surfaces are plotted for different locations of the feed and the subreflector. The second part of the report covers the design of an unfurlable, four-element system that will radiate four 60° beams, located with axes 60° apart, to cover a 120° sector in two orthogonal planes. Conical spiral elements were designed and tested and found to be satisfactory. Mutual coupling effects were measured and found to be negligible.

CONTENTS

ILLUSTRATIONS

1.0 INTRODUCTION

This report describes the work accomplished under contract number AF 33(657)-8709 during the first six-month period. This contract was divided into two phases, the first phase conforming to the original statement of work under the contract, and the second phase conforming to a revised statement of work. Effort on the first phase was suspended after approximately two months and began on the second phase after negotiation of the contract revision.

The overall objective of the contract is the advancement of unfurlable designs and techniques whereby antennas may be erected in space from a compressed or rolled up condition. The original contract called for investigation of highly directive, broadband, high power ECM antennas and associated hardware. Two unfurlable Cassegrain-type antennas were to have been built, one at X-band and one at K_a-band. The requirements were a half-power beamwidth of one degree, gain of 45 db, and operation over an octave bandwidth.

The revised contract calls for an unfurlable four-element radiating system forming four 60° beams with 3 db crossovers. These four beams will be individually modulated and used to determine stability of an orbiting vehicle by observation from the ground.

This report is divided into sections corresponding to phases of the contract.

2.0 CASSEGRAIN ANTENNA

2.1 General Description

The requirements of this phase of the contract specified investigation and development of techniques directed specifically to the application of highly directive, broadband, high-power ECM antennas and associated components such as feeds, transmission lines and connectors. It was intended that two models be built and tested, with the following design objectives:

a. Frequency: One model to operate at X-band, one model to operate at K_a-band.

b. Bandwidth: Maximum frequency bandwidth as a design goal, with a minimum acceptable bandwidth of 2 : 1.

c. Directivity and Resolution: Half-power beamwidths on the order of one degree and directivity of approximately 45 db above an isotropic radiator.

d. Power Handling: High power levels desirable, minimum of 100 watts average and 100 kw peak.

e. Polarization: Nominal.

f. Environment: The antenna must operate in a space environment.

The Cassegrain-type of antenna system is well suited to high-gain, narrow-beam applications. It consists of a main reflector, illuminated by a subreflector, illuminated in turn by the primary feed. (See Figure 1.) The shape and location of these components must be such that a constant path length exists from the feed to the main aperture, producing a uniform phase front. In most Cassegrain-type

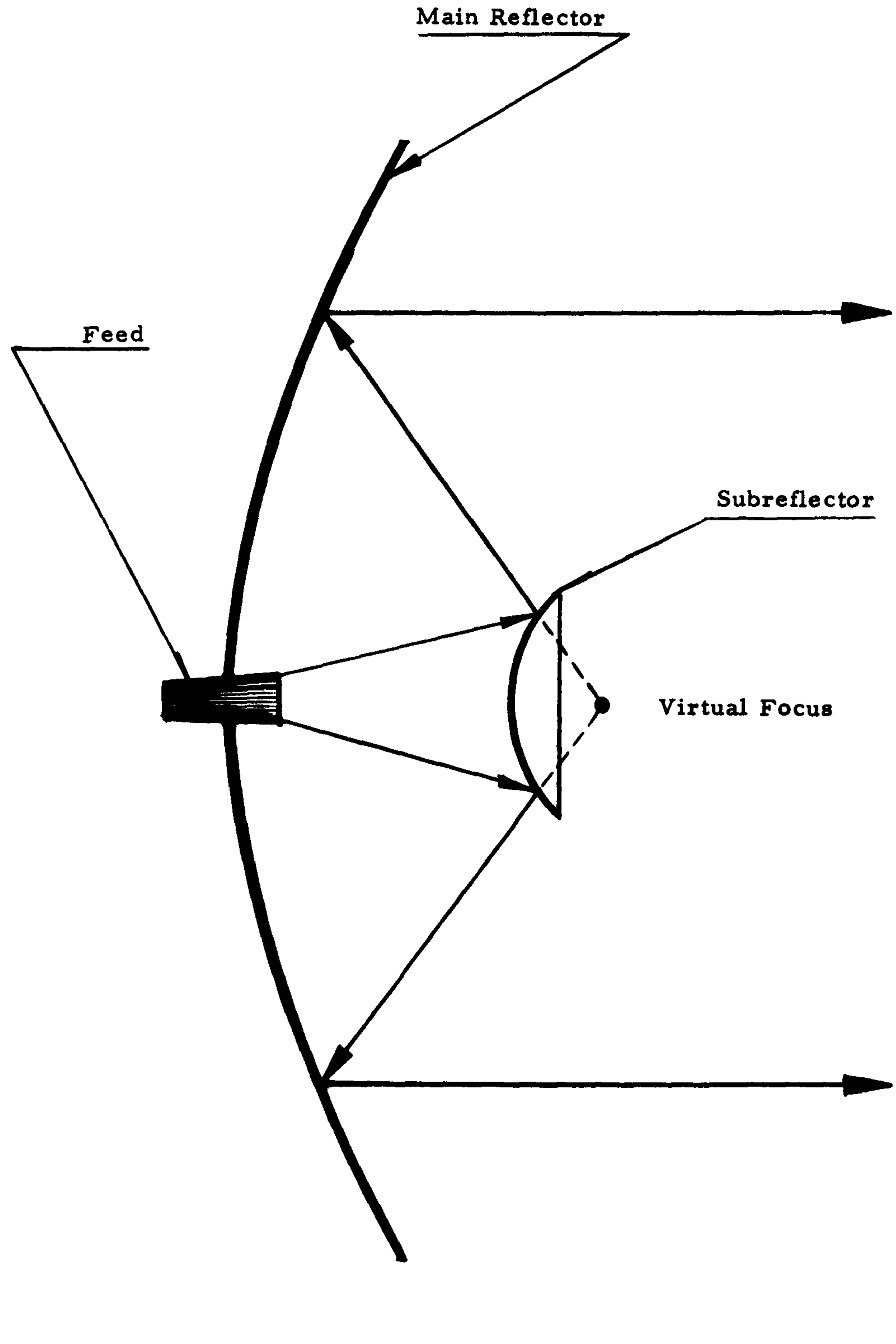


Figure 1. Basic Cassegrain System

antennas, this is accomplished with a parabolic main dish and a hyperbolic subdish. It was felt, however, that a sphere would be easier and less costly to fabricate to required tolerances in an unfurlable design and would have greater structural stability. Therefore, in the Unfurlable Antenna, the main reflector was constrained to a spherical shape, rather than parabolic, so that the shape of the subreflector had to be defined.

Mechanical design of this antenna was just begun under the original contract. It was decided that the feed and subreflector should be made in a rigid package, and that the main reflector would be a portion of an inflatable sphere. It was determined that this method of fabrication would be the least expensive in terms of maintaining tolerances and cause the least beam degradation due to mechanical deviations. The beam would be scanned by moving either the feed or the subreflector.

2.2 Subreflector Shape

When the main reflector of a Cassegrain system is spherical in shape, it is not possible to define the subreflector by a simple closed form relationship. The surface may be defined, however, in parametric form with respect to another variable.

Consider the geometry shown in Figure 2. If the system is cylindrically symmetrical about the axis OF, the problem becomes two-dimensional. The main reflector is a sphere of radius a with the center at O. A point-source feed is located at F. The subreflector crosses the axis at r_o. It is required to find a curve such that

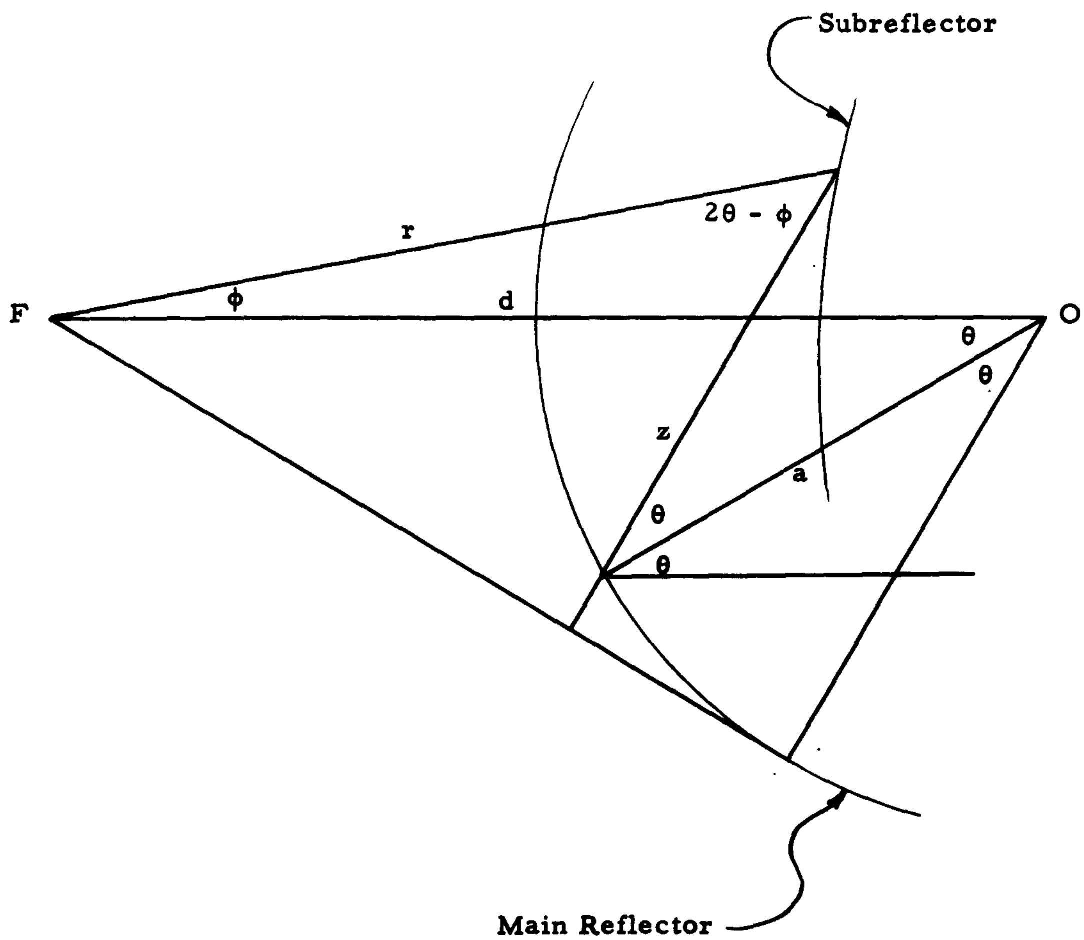


Figure 2. Geometry Used for Subreflector Computation

$$r + z + a\cos\theta = k$$

with k constant for all values of θ within a given range.

The equations for such a curve are

$$\tan\left(\theta - \frac{\phi}{2}\right) = \frac{d\sin 2\theta - a\sin\theta}{2r_o - d(1 - \cos 2\theta) + 2a(1 - \cos\theta)} \tag{1}$$

$$r = \frac{1}{2}\left[2r_o - d(1 - \cos 2\theta) + 2a(1 - \cos\theta)\right]$$

$$\cdot \left\{1 + \frac{(d\sin 2\theta - a\sin\theta)^2}{\left[2r_o - d(1 - \cos 2\theta) + 2a(1 - \cos\theta)\right]^2}\right\} \tag{2}$$

It can be shown that this surface $r(\theta), \phi(\theta)$ is a reflecting surface; i.e., the normal to the r, ϕ curve bisects the angle $(2\theta - \phi)$.

These equations were programmed for a digital computer and calculated for the following parameters, all normalized with respect to the sphere radius a:

$$0 \leq \theta \leq 45^\circ$$

$$d = 0.95,\ 1.00,\ 1.05$$

$$r_o = 0.30,\ 0.32,\ 0.34,\ 0.36,\ 0.38$$

These families of curves are plotted in Figures 3 through 5. The curves are plotted in terms of a unit sphere with the center toward the right and the feed toward the left. These curves may thus be scaled to a sphere of any size.

The maximum useful aperture of the spherical Cassegrain system is limited by the aberration present in large spherical reflectors. Incident rays parallel to the axis are not reflected to a single point; instead, they form an envelope known as a caustic. As can be seen in the plots, the subreflector surface, $r(\theta)$, $\phi(\theta)$ has a discontinuity at the intersection with the caustic, then doubles back in front of itself. The maximum angular aperture is indicated for each curve. Note that, for a given size sphere, the usable angular aperture becomes larger as the feed is moved behind the spherical reflector.

2.3 Aperture Blocking Study

The subreflector in a Cassegrain system must reflect radiation from the feed to the main reflector such that a uniform phase front exists over the main aperture. Therefore, the subreflector design must specify proper size, shape, and location.

The first consideration is to arrive at the proper size of the central reflector. This reflector, of course, has a screening effect as it is located in the path of the innermost reflected rays. A screening coefficient relating the unscreened to the total aperture area is expressed by

$$T = \frac{\pi b^2 - \pi a^2}{\pi b^2} = 1 - \left(\frac{a}{b}\right)^2$$

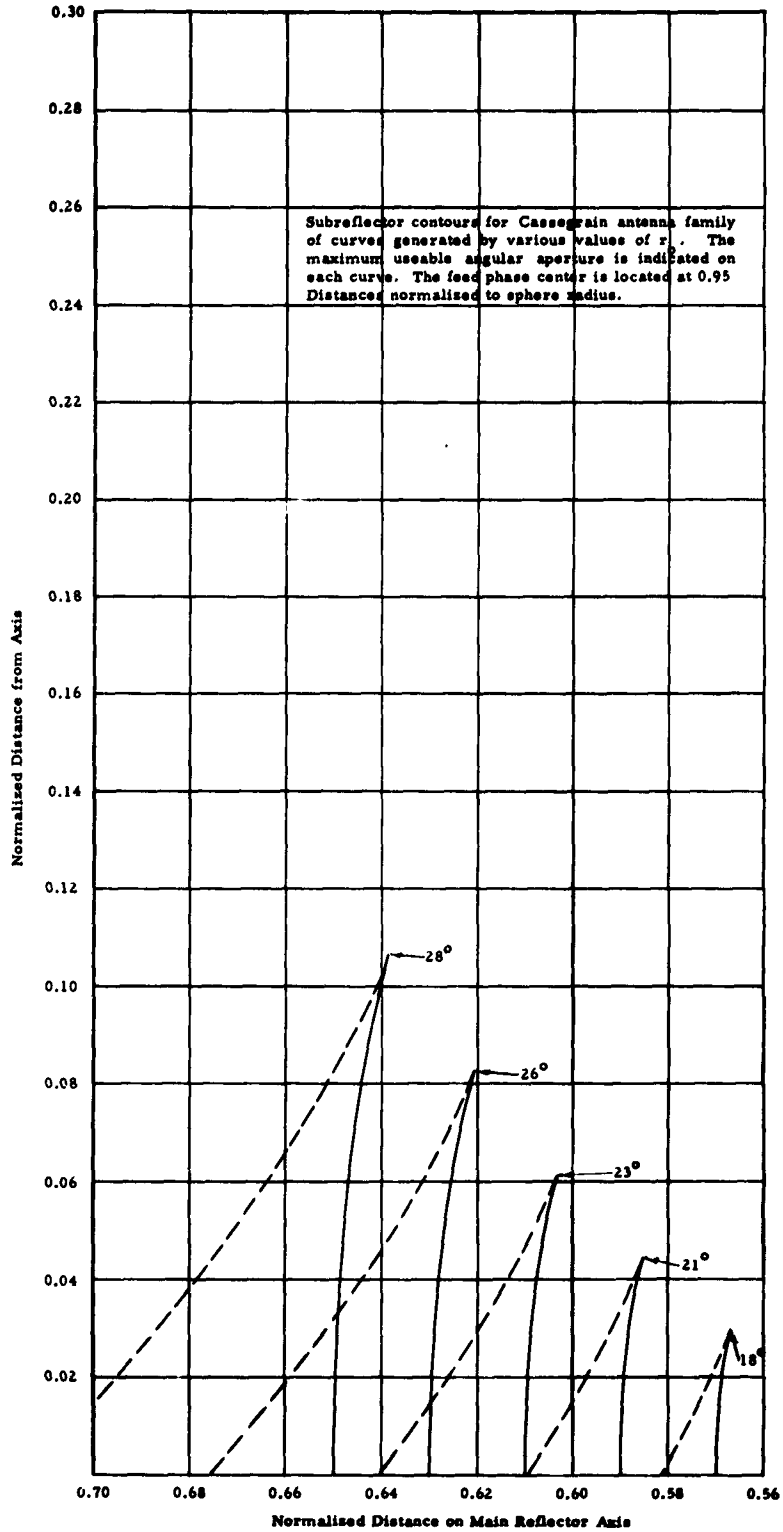


Figure 3. Subreflector Contours for F = 0.95

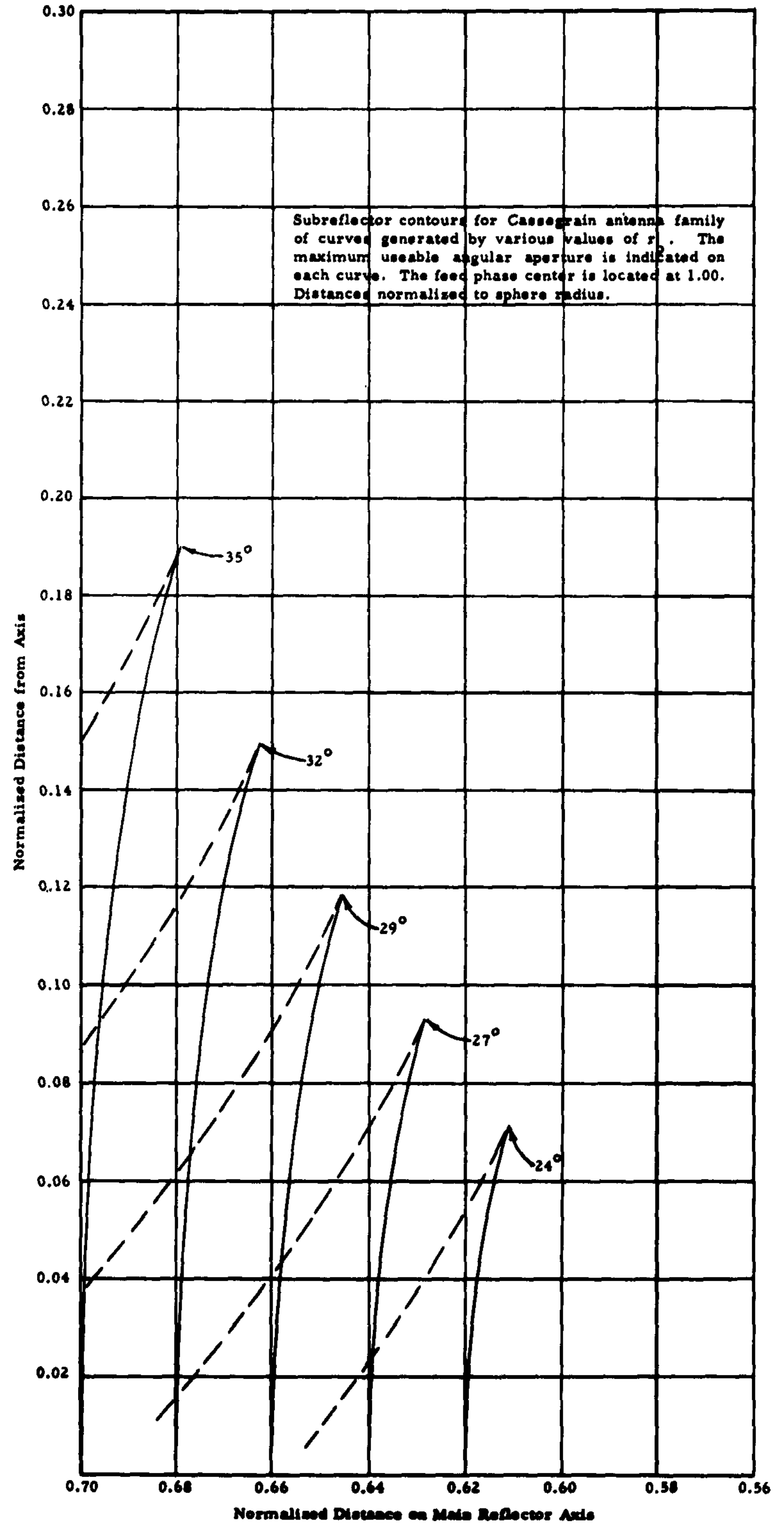


Figure 4. Subreflector Contours for F = 1.00

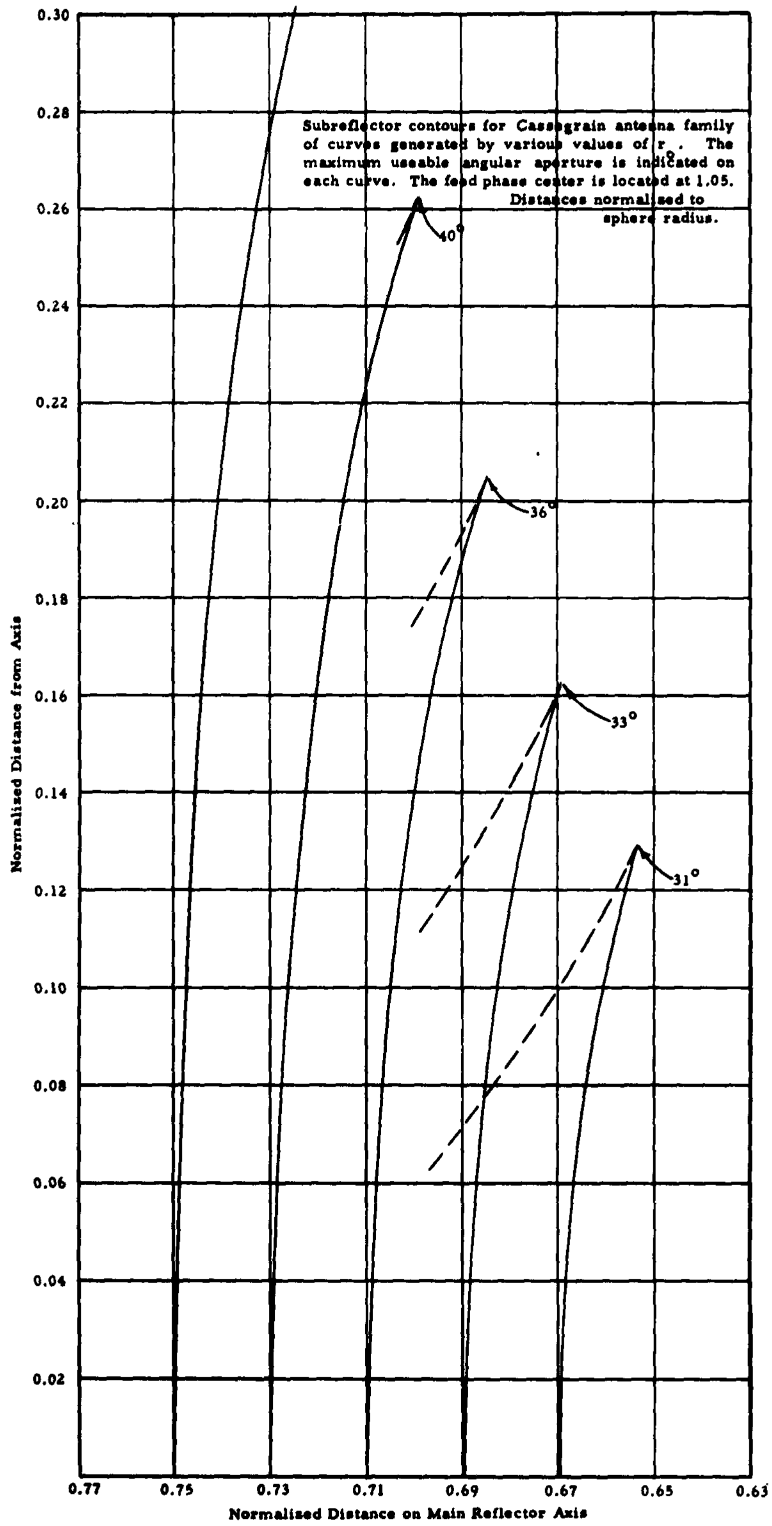


Figure 5. Subreflector Contours for F = 1.05

where

T = screening coefficient

a = subreflector half-aperture

b = main reflector half-aperture.

The obstructing reflector may be considered to produce a particular type of phase error. Assuming that the size of this reflector is small relative to the main reflector and that its presence does not modify the aperture distribution which would otherwise illuminate the main reflector, the obstruction can be regarded as producing a field out-of-phase with the distribution in the screened region. The problem of aperture blockage is considered for particular distributions with varying degrees of screening.

The expression for the far-field pattern of a circular aperture is

$$g(u, \phi) = a^2 \int_0^{2\pi} \int_0^1 f(r, \phi') e^{jur \cos(\phi - \phi')} \, r dr \, d\phi' \tag{3}$$

where $u = ka \sin \theta$. Assuming angular symmetry and further considering the aperture distribution, $f(r)$, independent of the angular coordinate, ϕ', the expression becomes

$$g(u) = 2\pi a^2 \int_0^1 f(r) J_o(ur) \, r dr \tag{4}$$

where $J_o(ur)$ is the Bessel function of order zero. For uniform phase and amplitude ($f(r) = 1$), integration of Equation (4) yields

$$g(u) = 2\pi a^2 \frac{J_1(u)}{u} \tag{5}$$

as the expression for the far-field pattern of an unobstructed aperture. Introducing an obstacle with normalized half-width of δ into Equation (4), the field expression for uniform illumination became

$$g(u) = 2\pi a^2 \int_\delta^1 J_o(ur)\, r dr$$

which can be rewritten as

$$g(u) = 2\pi a^2 \left[\int_o^1 J_o(ur)\, r dr - \int_o^\delta J_o(ur)\, r dr\right]$$

This expression illustrates the superposition of the out-of-phase field on the original distribution. Carrying out the integration and normalizing to the unobstructed case results in

$$g_o(u) = 2\left[\frac{J_1(u)}{u} - \delta\, \frac{J_1(u\delta)}{u}\right]$$

This equation is evaluated for values of δ of 0, 0.1, and 0.2 and plotted in Figure 6.

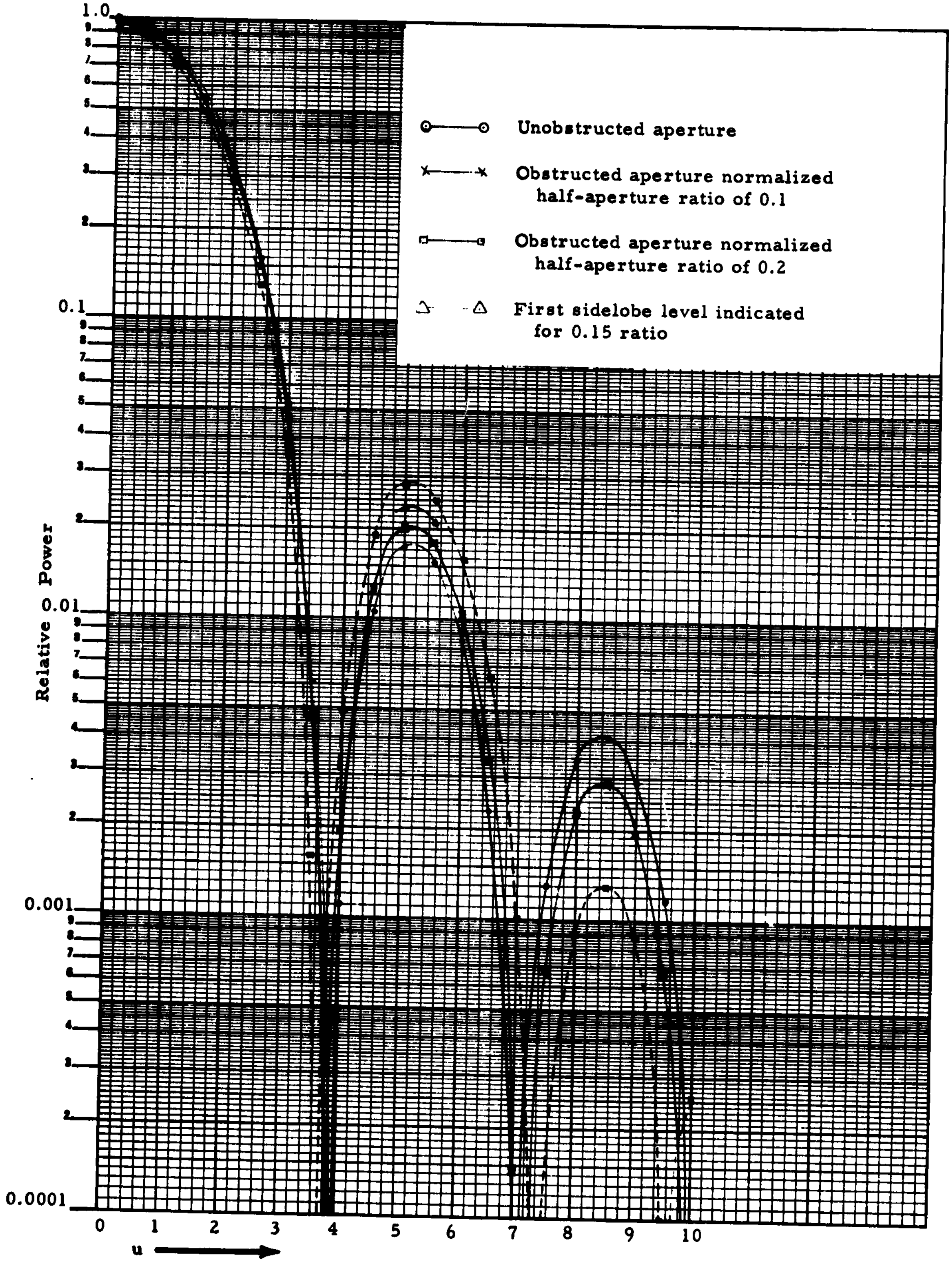


Figure 6. Aperture Blocking — Uniform Distribution

The general effect of aperture blocking is to degrade the pattern characteristics, but, as is indicated in Figure 6, this effect is quite small for small obstructions. For an obstacle with normalized half-width of $\delta = 0.2$, the pattern gain and beamwidth are decreased slightly, and the level of the first sidelobe is raised about 2 db.

A second case was analyzed for a tapered parabolic distribution function. Consider first the unobstructed condition for which the distribution can be approximated by

$$f(r) = K_1 + K_2(1 - r^2)$$

These constants can be evaluated by specifying the taper of the distribution function. For example, for a 10 db taper, at r equal to one,

$$f(r) = K_1 = 0.316$$

With the aperture distribution normalized to unity on axis (r equal to zero),

$$f(r) = 1 = K_1 + K_2$$

from which $K_2 = 0.684$. Inserting these values into the original equation

$$f(r) = 0.316 + 0.684(1 - r^2)$$

Setting $f(r)$ equal to this expression in Equation (4), results in

$$g_o(u) = 2\pi a^2 \left[\int_o^1 \left\{ 0.316 + 0.684(1 - r^2) \right\} J_o(ur)\, r dr \right]$$

which integrates to give

$$g_o(u) = 2\pi a^2 \left\{ 0.316 \frac{J_1(u)}{u} + \frac{1.368\, J_2(u)}{u^2} \right\}$$

For the blocked aperture case with an obstacle half-width of δ and a similar parabolic distribution, the far-field patterns for the obstructed aperture can be arrived at by evaluating the contribution in the blocked region and combining this properly with the pattern computed for the unobstructed condition. In the blocked region

$$g(u, \delta) = 2\pi a^2 \left\{ \int_o^\delta - \left[k_1 + k_2(1 - r^2) \right] J_o(ur)\, r dr \right\}$$

which becomes

$$g(u, \delta) = -2\pi a^2 \left\{ \frac{(k_1 + k_2)\, \delta\, J_1(\delta u)}{u} - \frac{k_2 \delta^3 J_1(\delta u)}{u} + \frac{2\delta^2 k_2 J_2(\delta u)}{u^2} \right\}$$

This equation has been evaluated for values of δ equal to 0.1 and 0.2 and combined with the pattern for no obstacle. The pattern is plotted in Figure 7. The pattern degradation is still slight, but is somewhat greater than for the case of uniform illumination. For an obstacle with normalized half-width $\delta = 0.2$, the level of the first sidelobe is increased by about 4.5 db.

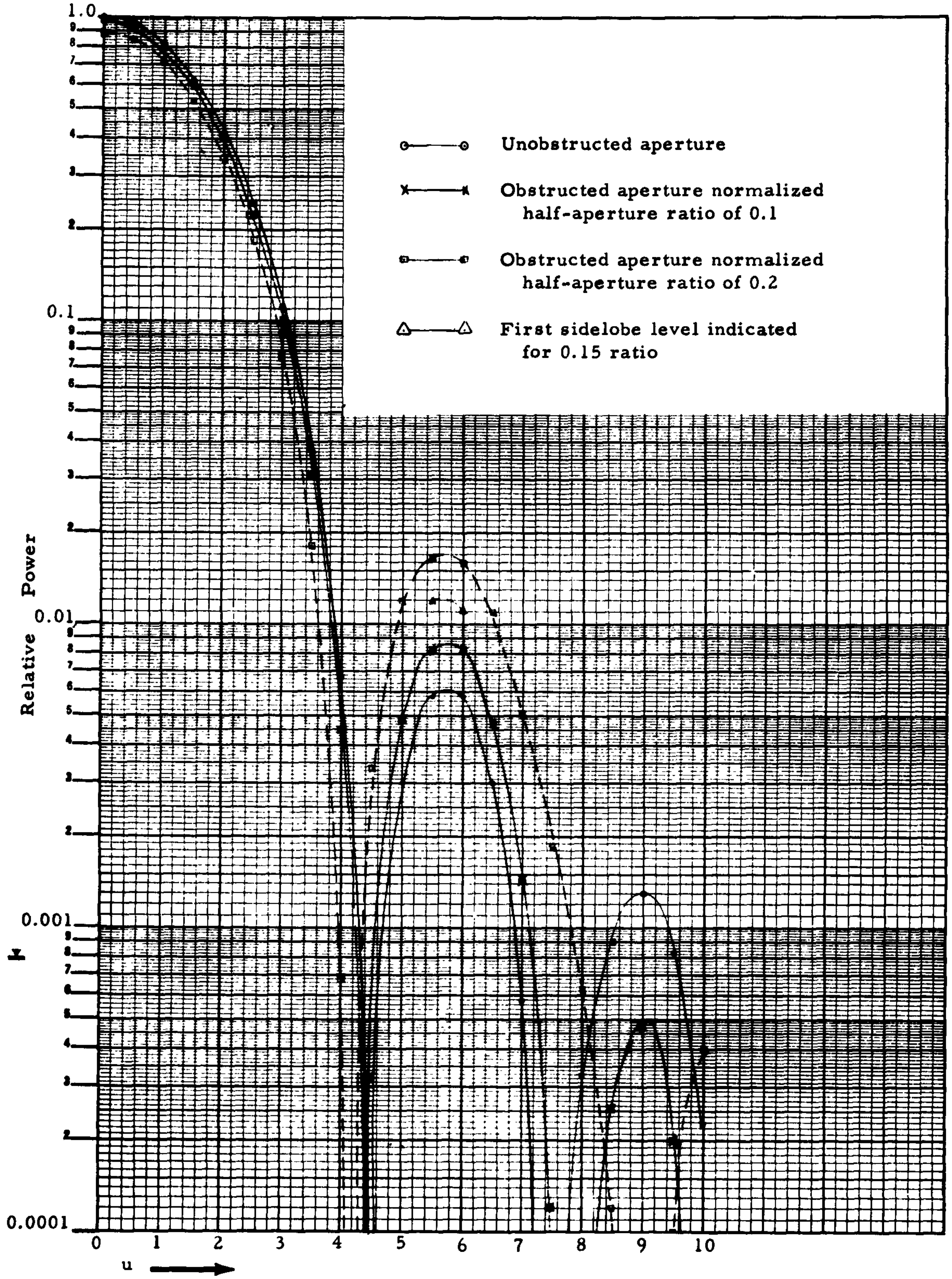


Figure 7. Aperture Blocking — Tapered Distribution

While the effects of aperture blocking are not serious, it is usually desirable to minimize them as much as possible. This can be done by proper choice of subreflector location and feed point location. The minimum subreflector size is determined by angular coverage and other design requirements.

This is the point at which effort was suspended on the original contract. Additional studies that were to have been made include analysis of errors caused by spherical aberrations and mechanical deviations, and analysis of scanning the beam by moving the feed or the subreflector.

3.0 REVISED DESIGN

3.1 System Design

Under the revised work statement, the objective of the contract is to produce a system package that will unfurl in space and radiate four individually-modulated beams. It is planned to use these beams to determine stability of the system through observation from one or more ground stations.

The system concept is shown in Figure 8. The antenna consists of four radiating elements located with 60° between their respective axes, such that each element covers one quadrant of a $120^{\circ} \times 120^{\circ}$ volumetric sector. The beamwidth of each element is 60° at the 3 db points, giving a 3 db crossover and 120° coverage in two orthogonal planes. Each beam will be amplitude-modulated at a different audio frequency — 700, 800, 900, and 1000 cps, respectively. An observer at a ground station will know by the modulation frequency which of the four beams is pointed toward him. By noting the rate at which the beam moves, or the relative amplitudes of two or more of the beams, the observer will be able to determine the stability of the orbiting vehicle.

The transmitted power is required to be a minimum of one watt average, at a frequency in the 2200 to 2300 Mc telemetry band. The entire package must be contained in a volume of approximately one cubic foot and weigh less than fifty poinds. The antenna will have to be unfurled once in space, and the system will have a life expectancy of approximately 300 hours.

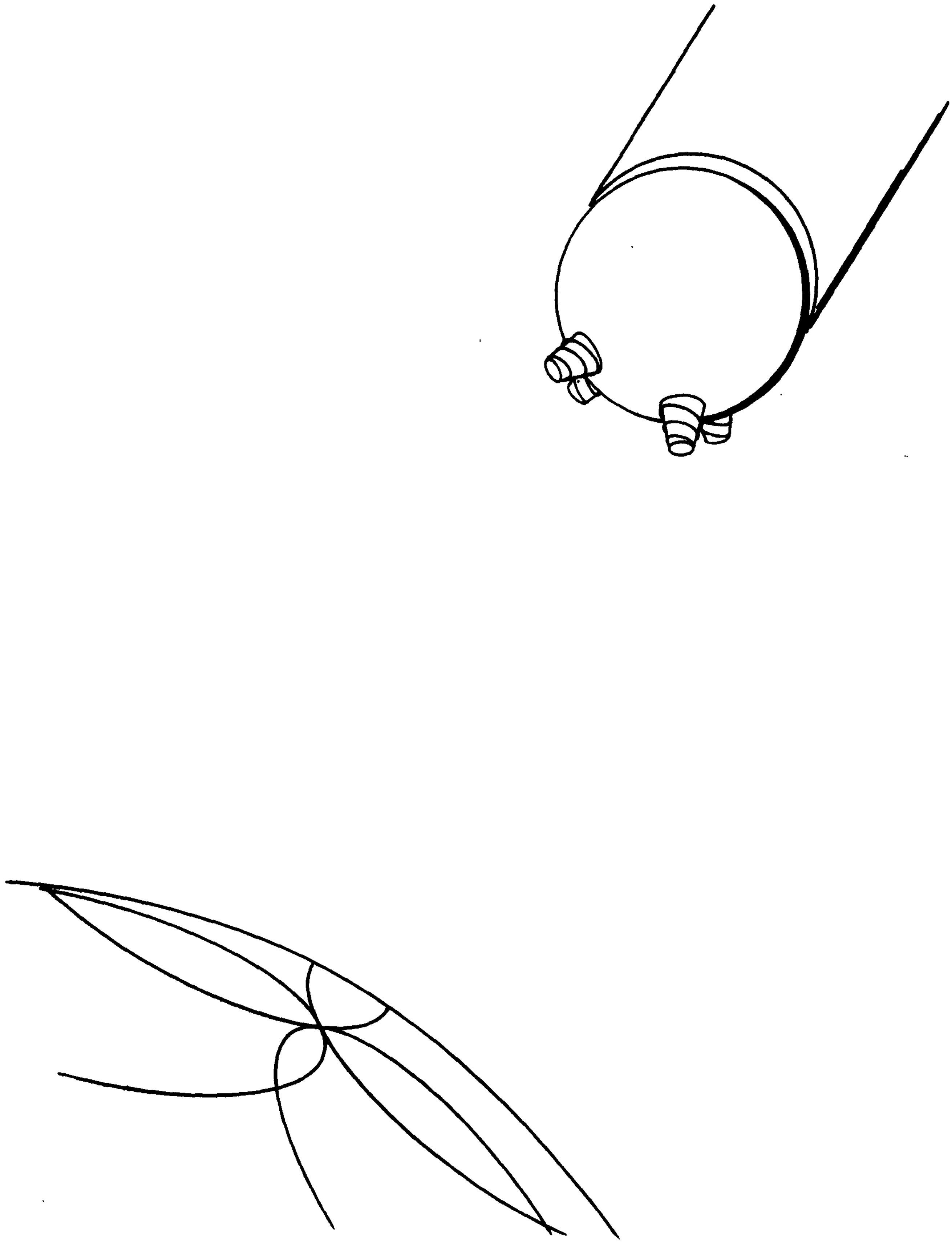


Figure 8. Four Element Unfurlable Antenna System

In addition to the transmit mode, the system must have a receive mode, in which the four elements form a receiving array operational from 1200 to 2200 Mc. The system will be switched from one mode to the other by a signal from the ground. In the receive mode, the received signal will be switched to a receiver in the vehicle.

The system design, shown schematically in Figure 9, consists of a transmitter whose output is divided among four separate modulators and four radiating elements. A power converter with a 28-volt dc input supplies the required power to the transmitter and the modulator drivers. Two separate corporate feeds are used, a narrow-band feed at the transmit frequency, and a wideband receiving feed. This will eliminate the loss caused by the modulators in the receive mode. SPDT mode selector switches are located just behind the radiating elements. The corporate feeds will be simple stripline hybrid circuits. The other components are discussed in the following sections.

3.2 Radiating Elements

The individual radiating elements are required to have 60° beamwidth, circular polarization, and must operate from 1200 to 2200 Mc, a frequency bandwidth of over 1.8 to 1. The elements designed to meet these conditions are conical log-periodic spirals. A conical spiral can be made to radiate in an axial mode, independently of any ground plane, with the beamwidth controlled by the cone and spiral parameters, particularly the cone angle and the number of turns in the spiral. Operation over a wide frequency band is obtained through the log-periodic property, characteristic of a class of so-called "frequency independent" antennas.

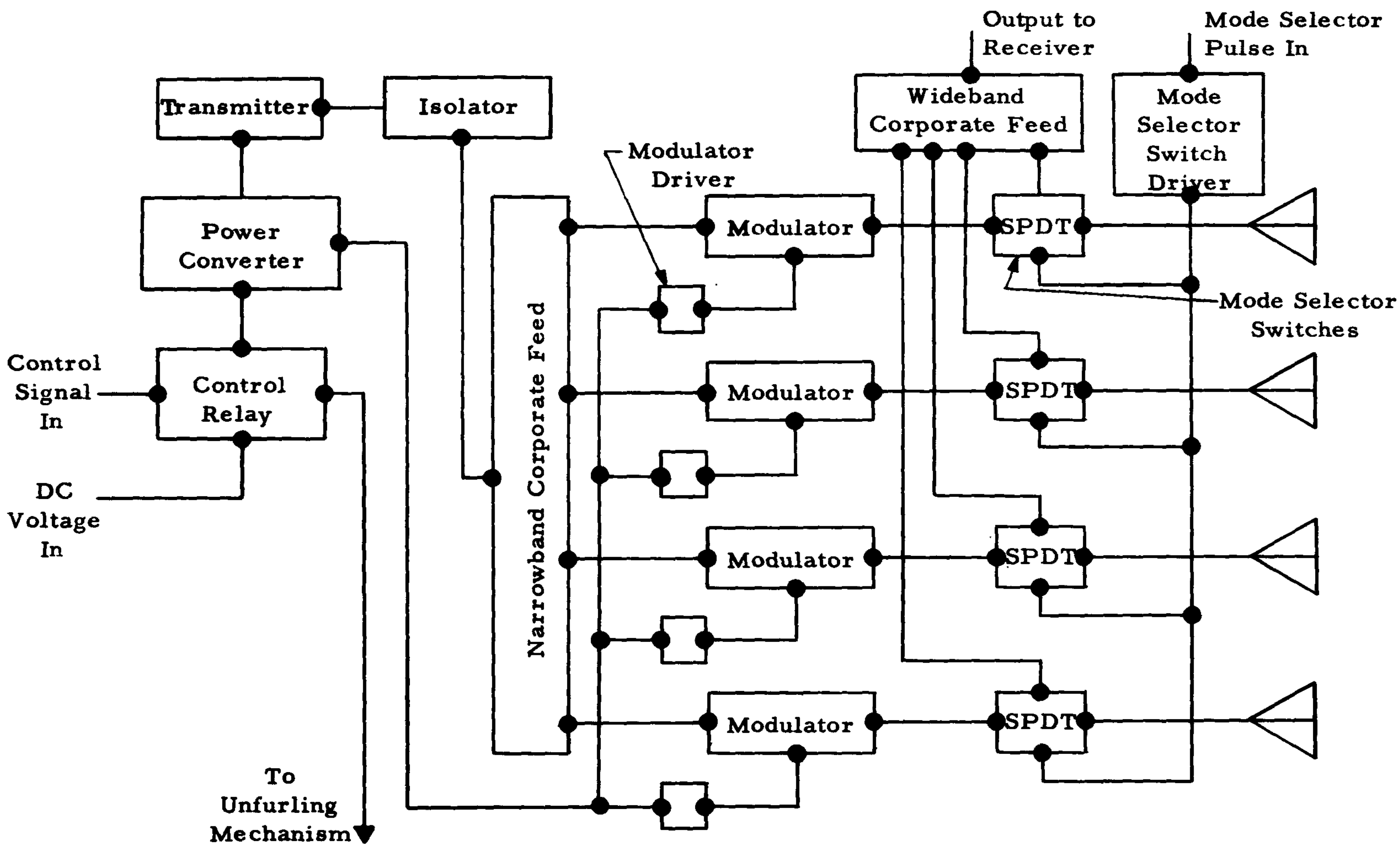


Figure 9. Unfurlable Antenna System Schematic

A conical spiral, or conical helix, as it is commonly called, is shown in Figure 10, along with defining parameters and nomenclature. The pitch angle α is taken to be constant. This leads to logarithmic spacing between turns and eliminates fabrication difficulties caused by a varying pitch angle. The spiral is defined in terms of slant length from the apex versus rotation angle. This has been derived as follows: Consider an elemental length of the helix in Figure 10.

$$\sin\gamma = \frac{a}{\rho}$$

$$\tan\alpha = \frac{d\rho}{a\,d\phi}$$

$$\frac{d\rho}{\rho} = \sin\gamma \ \tan\alpha \ d\phi$$

Integrating

$$\rho = \rho_o e^{2\pi n \sin\gamma \ \tan\alpha}$$

It has been found empirically that d_1 must be approximately $\frac{3}{8}\lambda_1$, and d_2 about $\frac{1}{4}\lambda_2$, where subscripts 1 and 2 refer to lower design frequency f_1 and the upper design frequency f_2. Thus the element is completely defined.

Several conical elements were built with different cone and pitch angles in order to determine the optimum design for 60° beamwidth and low axial ratio. The first elements tried were single copper

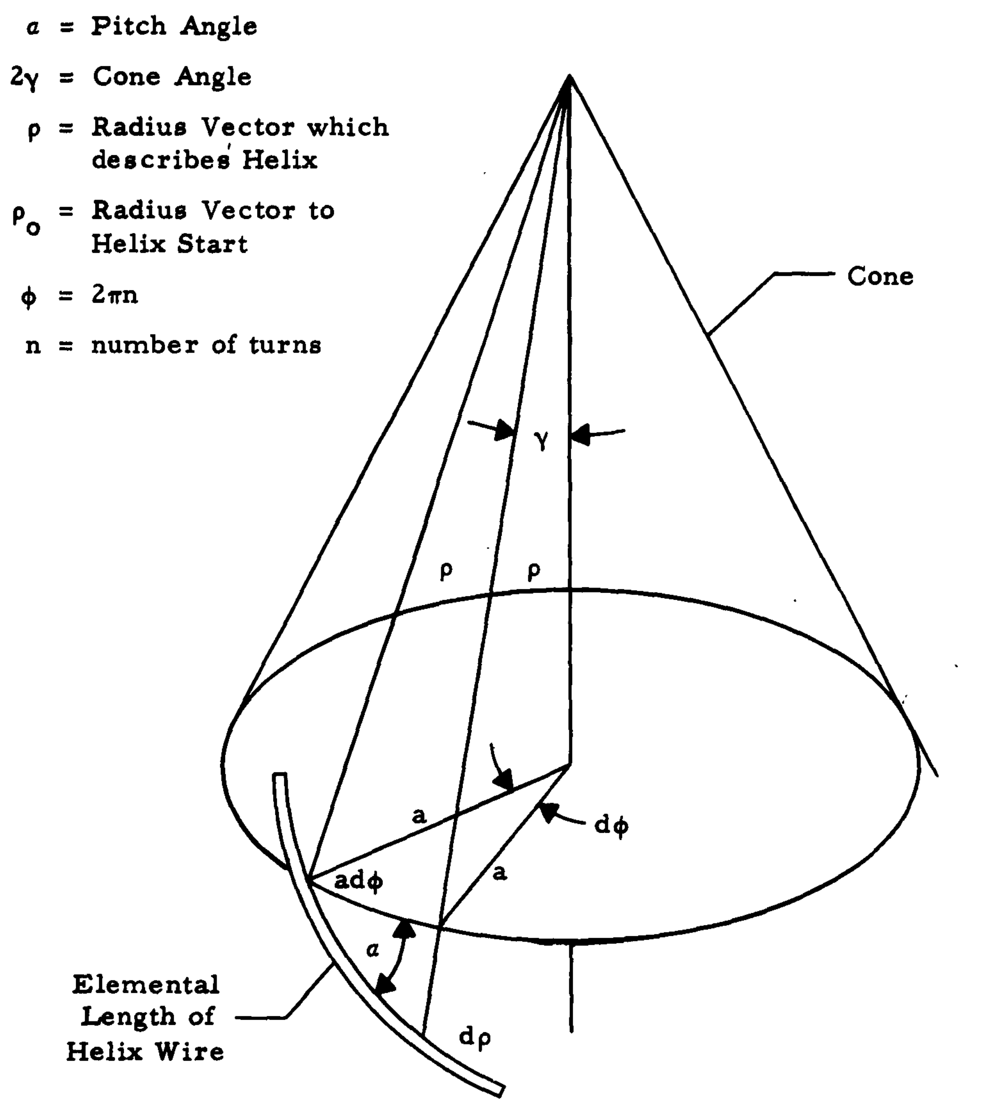


Figure 10. Sketch of Parameters for Derivation of Conical Helix

wire spirals, unbalanced, and fed either at the apex or at the base. The cone angle was 90°, the pitch angle 5.5°, base diameter 7.5", and there were six turns.

These elements proved unsatisfactory. The beamwidth varied rapidly with frequency from 50° to 80°, over the band. The axial ratio varied from 1 db to 3.5 db. The beam itself showed ripples and asymmetry which varied over the band. The VSWR was high at the lower end of the band.

Efforts were made to improve the performance by varying the spacing between the ground plane and the first turn of the helix, and various matching techniques were tried. The input impedance of the helix was measured for several different conditions. The characteristics could be varied, but not substantially improved.

A six-turn helix with a 21° cone angle and a 12° pitch angle, fed at the base, was constructed. The response was good at the low end of the band, but deteriorated rapidly as the frequency increased. The beam became quite asymmetrical, and a secondary lobe appeared off-axis for one polarization.

It was concluded that a longer element was required for better control of the beam shape. The length was increased to approximately 8", with a cone angle of 21°. This angle was held constant, but the pitch angle, number of turns, type of conductor, and method of feeding were tried in various combinations, none of which proved satisfactory. An experimental model is shown in Figure 11.

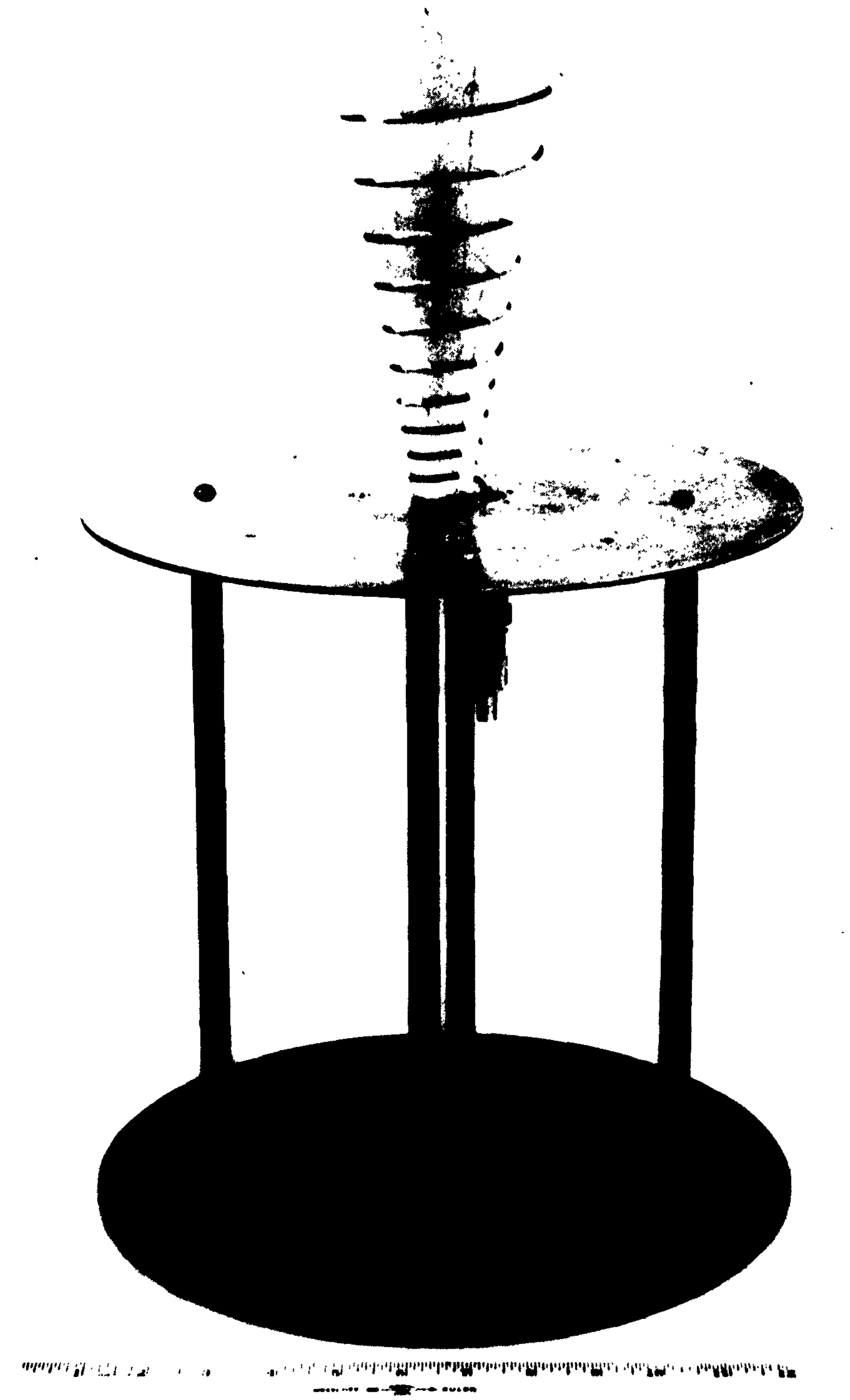


Figure 11. Photograph of Unbalanced Single-Wire Helix

After this model, the unbalanced spiral was discarded in favor of a balanced model. In this case, a balanced feed is required for optimum performance, and the bandwidth of the antenna is limited by the bandwidth of the feed. To achieve a balanced structure, the feed cable was used as one arm of the spiral. At the origin, the center conductor is tied to a dummy cable which forms the opposite arm. The ends of the antenna arms carry very little current, except at the lowest operating frequency, so the arms themselves act as a balun. Two types of structures were used. In one, both the feed cable and the dummy arm were made of ordinary flexible coax cable with the outer insulation stripped off. This type is shown in Figure 12. In another, both arms were made of 1/4" wide copper tape, 0.003" thick, with the feed cable bonded to one arm and carried to the apex. A sketch of the feed point configuration is shown in Figure 13.

Several different balanced conical spirals were built with 21° cone angles. The major problem was asymmetry and irregularity in the beam shape at frequencies of 2000 Mc and above. Better results were obtained when smaller cable was used. RG-174/U proved satisfactory. The best results to date have been obtained with a balanced seven-turn helix with 21° cone angle, 9° pitch angle, and RG-174/U cable for both arms. The beamwidth, however, is still slightly greater than is desired.

After the required characteristics for a single element were achieved, an array was built to measure the sum patterns and to measure the mutual coupling between elements. A four-sided pyramidal ground plane, 10" on a side, and sides inclined at 30° with the horizontal, was built to make these measurements. A sketch of this ground plane is shown in Figure 14. The helices were mounted on dielectric

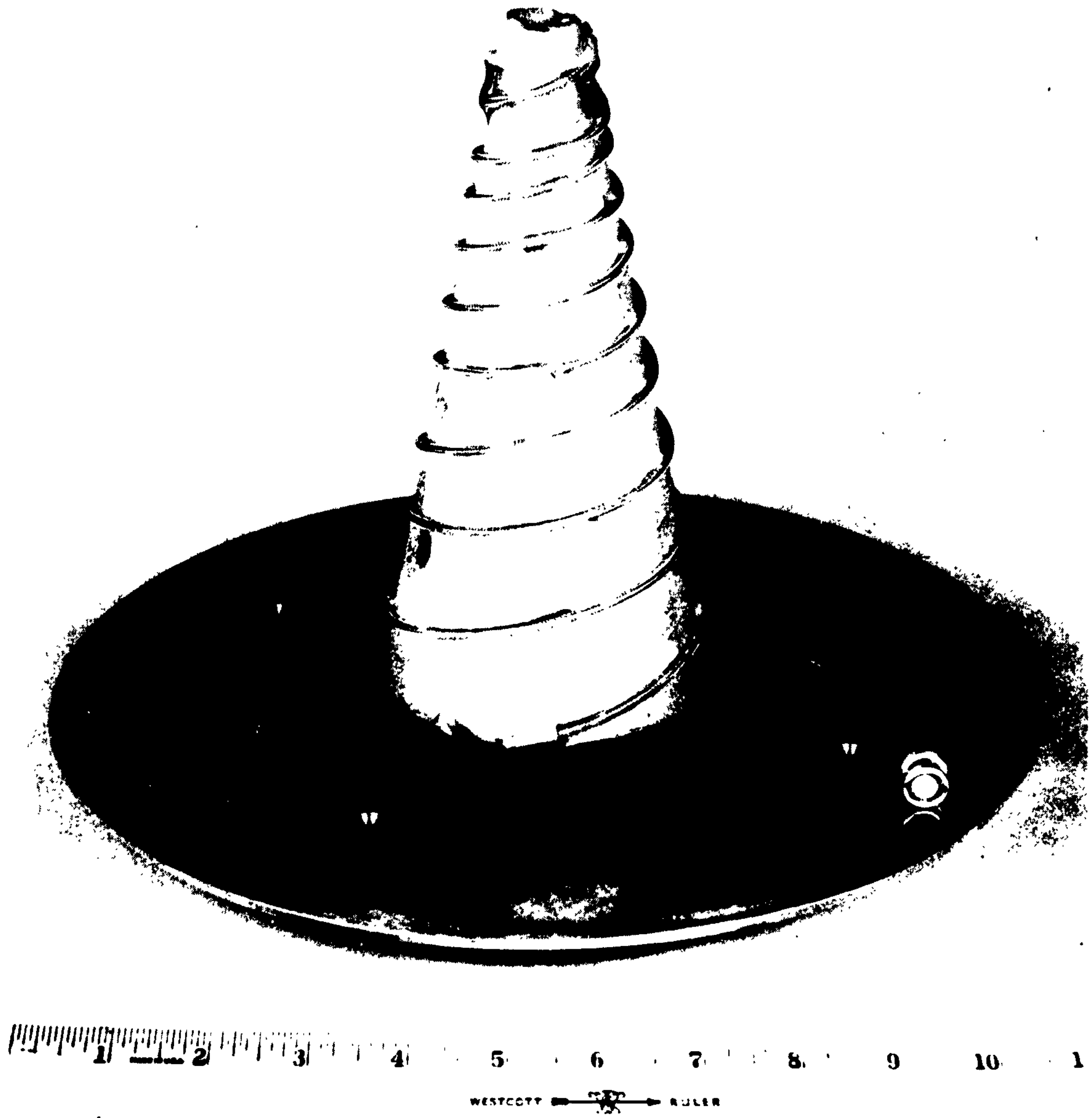
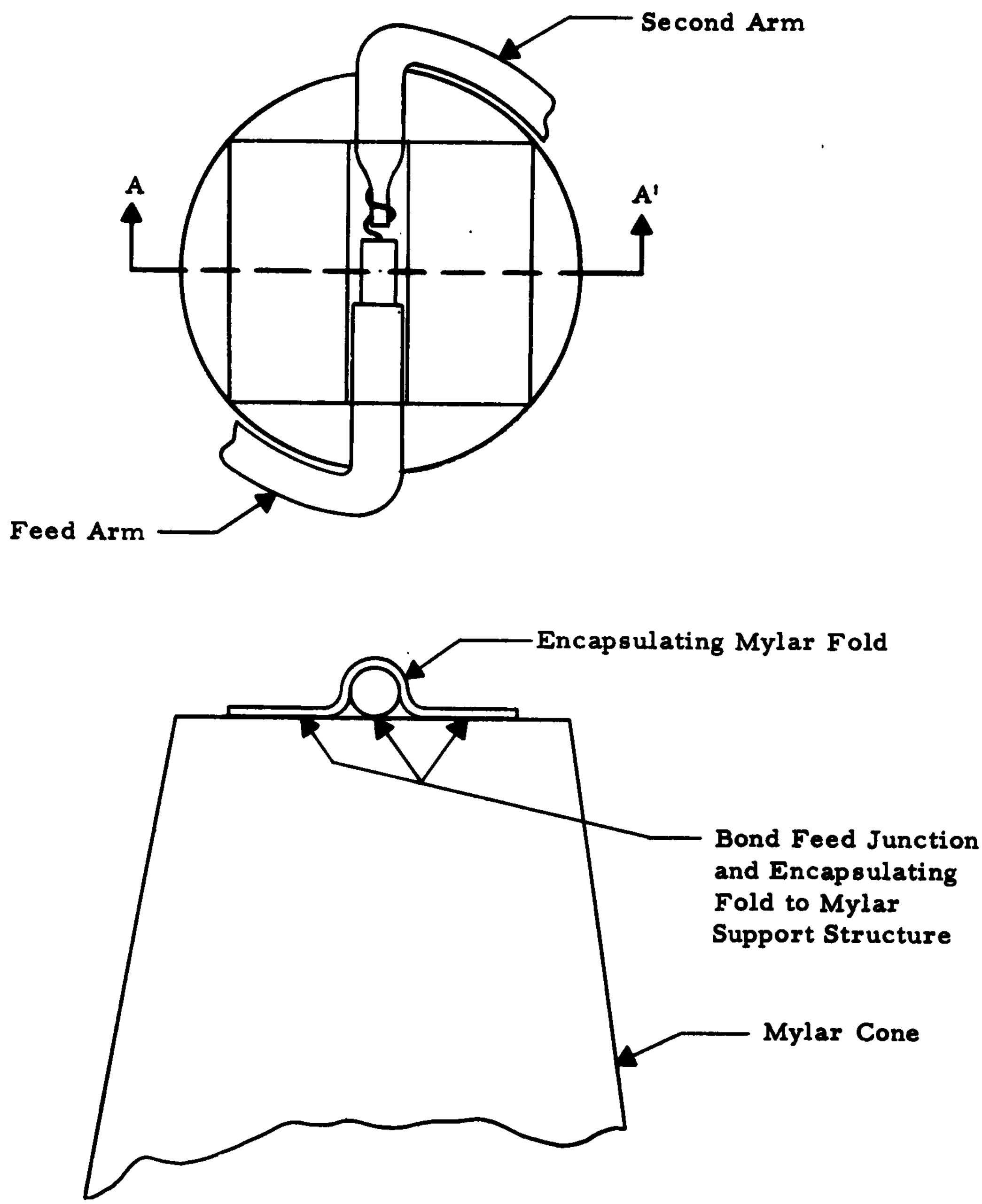


Figure 12. Photograph of Balanced Helix



Partial Section View A-A'

Figure 13. Sketch of Feed Point Configuration

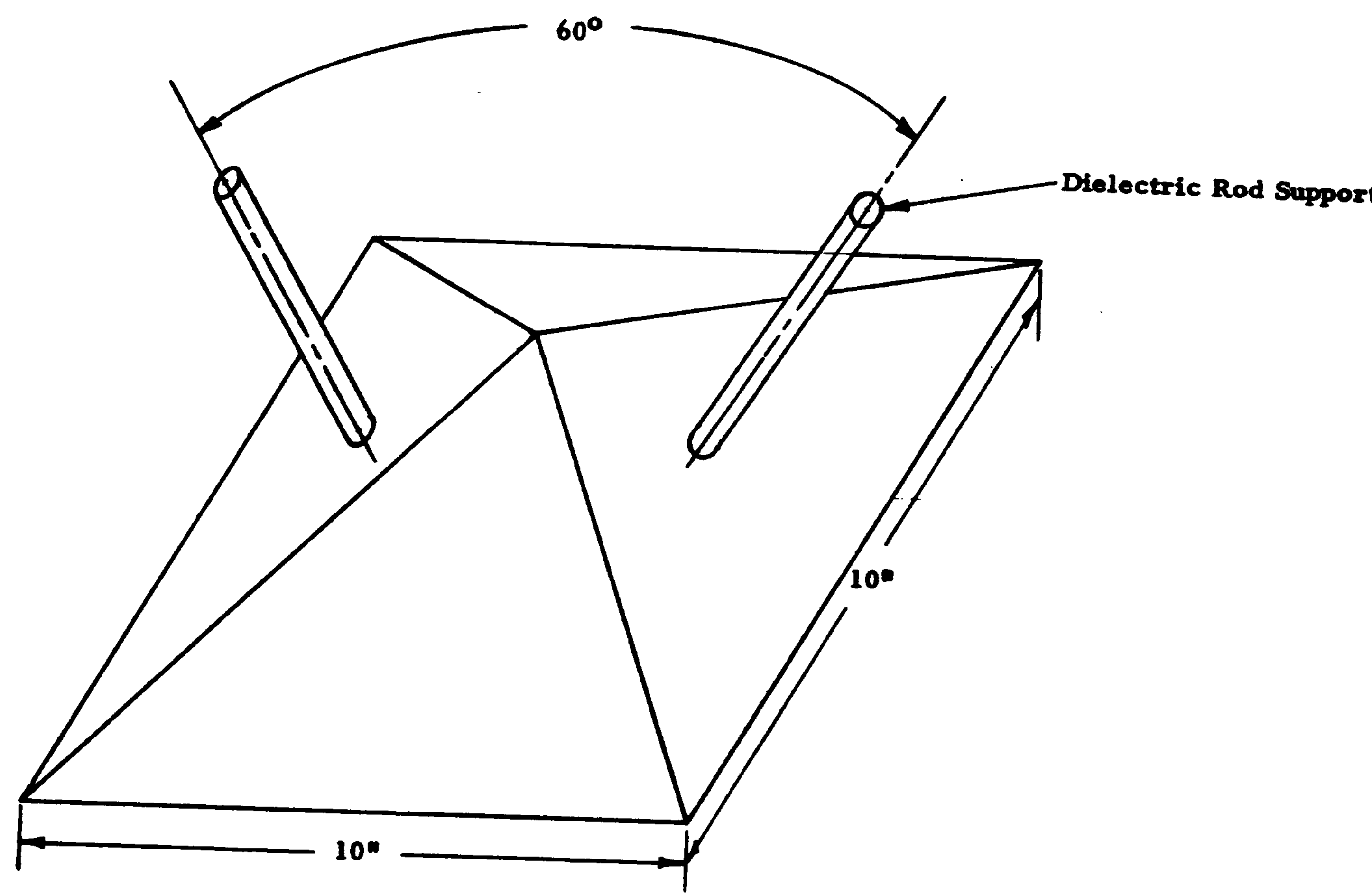


Figure 14. **Pyramidal Ground Plane Used for Helix Patterns**

rods at the center of each side, making a 60° angle between cone axes, and fed from behind through small holes in the ground plane.

The effects of mutual coupling were noted by first placing a single element on the ground plane and taking a pattern. Then a second element, oriented in the same phase, was placed on the opposite side of the ground plane and terminated in a 50-ohm load. The pattern of the first element was then repeated and the differences ascribed to the presence of the second element. A typical pattern is shown in Figure 15, and it can be seen that the differences are negligible. This was true in all mutual coupling measurements made.

The combined sum patterns were measured by joining the two elements through a coax "tee". A line stretcher was inserted in one arm for phase adjustment. This adjustment could also be made by rotating the elements. The resulting patterns display an interferometer effect, shown in Figure 16, that becomes more pronounced as the frequency increases. This is an expected result because as the frequency increases, the radiation phase center of the helix moves toward the cone apex. Thus there is an increase in distance between elements in terms of wavelengths, plus the aggravating effect of a physical increase in distance between phase centers because of the 60° orientation.

3.3 Unfurlable Package Design

The radiating elements will be mounted on an inflatable sphere with a metalized surface acting as a ground plane. The sphere will be designed to erect itself in space at a given signal. Investigation of materials, fabrication techniques, erection techniques, and rigidization will be performed prior to construction of prototype models.

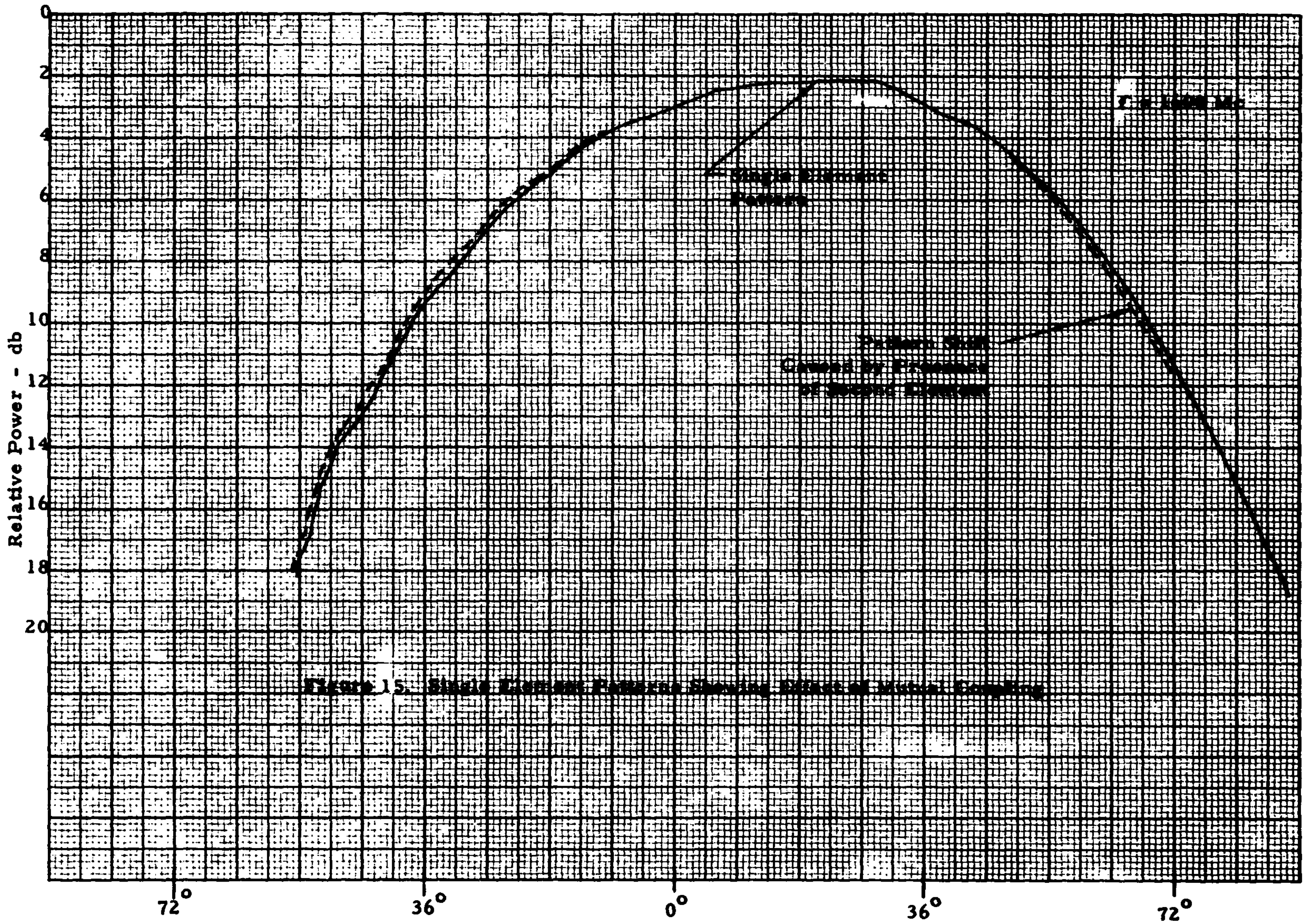


Figure 15. Single Element Patterns Showing Effect of Mutual Coupling

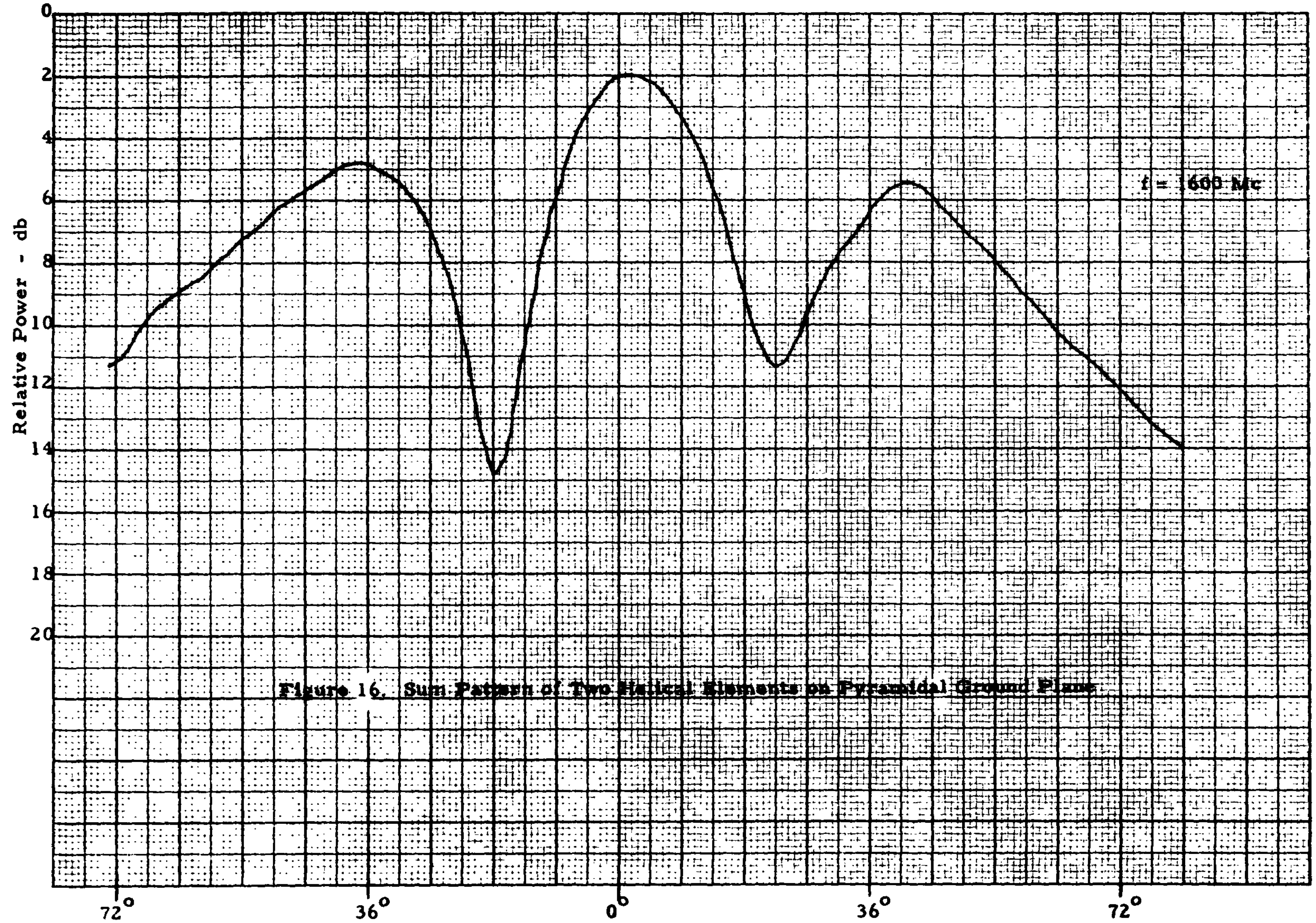


Figure 16. Sum Pattern of Two Helical Elements on Pyramidal Ground Plane

This phase of the program will be done by G. T. Schjeldahl Company under subcontract to American Systems Incorporated. As of 17 December 1962, the purchase order for the subcontract had been approved by the local Air Force Management Office, and G. T. Schjeldahl Company had been notified to start work.

3.4 Transmitter Design

The antenna system includes a 1 watt transmitter in the 2200 to 2300 Mc band. Commercially available oscillators, with little or no modification, will meet the requirements. Both solid-state and triode cavity sources are under consideration. A solid-state source has the advantages of smaller size and lower input voltages. Triode cavity sources, on the other hand, can provide more power, are more efficient, and are more fully developed for missile applications. Quotations will be requested on the transmitter, and purchase will be made on this basis.

3.5 Modulators

Each of the four transmitted beams will be sinusoidally modulated with approximately 30 percent amplitude modulation at audio frequencies of 700, 800, 900, and 1000 cps. The modulation will be accomplished with diode modulators in a stripline circuit. Several types are being considered. The simplest type is an in-line reflective attenuator, and it is believed that this will be satisfactory. An absorptive attenuator can be built by putting matched diode terminations on isolated arms of a 3 db hybrid. This type is matched under all conditions.

The reasons for using sine-wave modulation are to conserve microwave power and to eliminate harmonic sidebands. If the power loss and the presence of sidebands could be tolerated, square-wave modulation could be used and could be achieved by a simple SPDT or SPST switch. It is felt that square-wave modulation is satisfactory, but less desirable than sinusoidal modulation.

3.6 Measurements

The measurements made on this portion of the program utilize common techniques. VSWR and impedance measurements were made with a Hewlett-Packard Model 805-C slotted line, bolometer and Model 415-B standing wave indicator. The pattern measurements were made on an outdoor range with the test antenna on a three-axis mount. A Scientific Atlanta pattern recorder and mount controls are used with this equipment.

4.0 CONCLUSIONS

During the first portion of this program, the Cassegrain system was studied to the extent required to provide definitive design conclusions. An unfurlable Cassegrain system with a spherical main reflector is a feasible approach to a high-gain antenna for an orbiting vehicle. Although the subreflector cannot be defined by a single equation in closed form, it can be defined in parametric form amenable to calculation by a digital computer. The pattern degradation caused by aperture blocking is relatively minor for a small subreflector.

During the second part of this program, effort was concentrated mainly on the design and orientation of the radiating elements. A 21° conical helix approximately eight inches long will produce the desired 60° beamwidth. When the cones are oriented at 60° spacing between axes, pointing away from the center, the mutual coupling is negligible. This configuration, however, is not well suited for the generation of a good four-element sum pattern over 1.8 to 1 frequency band required in the receive mode. Experimental evaluation of alternate element mounting configurations is currently underway.

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